計算機ネットワークの適応経路制御方式　Potential Routing

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高いネットワーク性能を得るためには、よい経路制御とフロー制御が必要不可欠である。本論文では計算機ネットワークのパケット転送方式に応用するための新しい適応経路制御方式　Potential Routing を提案する。Potential Routing では、計算機ネットワークを電気回路網とみなし、出発地から到着地までをノード間の電位差にそってパケットを流す。ノードの電位はキルヒホッフの第一法則で求め、ネットワークの混雑度によって経路を決定する。Potential Routing は次の特徴をもつ。（1）経路制御を行う場合に、ネットワーク全体の構造を反映した制御が可能であり、またどのような構成のネットワークにも応用可能。（2）制御テーブルはキルヒホッフの法則から得られる連立1次方程式で簡単にかつ高速に求められる。（3）ピンポン現象やループ現象を引き起こさない。（4）常に最短経路を与えるという保証はないが、ほとんどのネットワーク構造で最短経路を与える。

AN ADAPTIVE NETWORK ROUTING METHOD - POTENTIAL ROUTING

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To realize high network performance, adequate routing and flow controls are indispensable for the communication of information among computing nodes. We propose a new routing control method, called potential routing, for packet communication in computer networks. Potential routing models a computer network as an electrical circuit, and packet routing from a source node to a destination node is performed according to the potential differences between adjacent nodes. The node potentials are first given by Kirchhoff's law and are then dynamically adjusted according to the traffic situation. Potential routing has the following features: (1) It can be applied to arbitrary network topologies. It takes account of the global network topology in determining the route. (2) The routing table is easily and therefore quickly computed by Kirchhoff's law, using simple simultaneous equations. (3) It does not involve the ping-pong (loop) problem. (4) It is not guaranteed always to give the shortest path, but it actually does so in most cases. By simulation, we verified that potential routing shortens transmission delays, especially when the traffic is heavy or unbalanced.

1. Introduction

Numerous routing methods have been proposed for various types of network configuration, traffic flow, and node processing ability. They can be roughly classified into the fixed-routing control and adaptive-routing control methods.

In actual computer networks, the amount and distribution of the traffic vary with the course of time, and nodes or links may fail. In such an environment, adaptive routing leads to a more satisfactory result than fixed routing, if the traffic situation is accurately reflected in the routing control. In adaptive routing, the control complexity at nodes should be taken into consideration, and the algorithm should not be too complicated.

The present paper presents a new routing method, potential routing, which is a packet-based adaptive-routing control method using an electrical-circuit model. Routing control is performed according to the potential differences between adjacent nodes. Potential routing has the following features:

1. It can be used for the networks with any topology, and take account of the global network topology in selecting appropriate routes.
2. The node potential is determined by solving a system of equations derived from Kirchhoff's law. Since a physical electrical system is considered, there always exists a unique solution, which makes it easy to cope with modifications of the network topology such as additions or deletions of nodes or links. In addition, even if the size of equations would become large for a huge network, the generation of the routing table can benefit from the computation technique, which is specially designed for a sparse matrix.
3. It does not cause the ping-pong (looping) problem, since the packet is always transferred in the direction of the lower node potential.
4. It can be applied only to networks with direction-independent links.

2. Algorithm

We describe a procedure for finding the routing path using the simple example shown in Fig. 1. For simplicity, but without losing generality, we assume that all links have the same distance (or cost).

First, an electrical current source is connected between the source node (node 1) and the destination node (node 8). The potential of each node is then calculated by Kirchhoff's law, with the potential of the source node being defined as 0 V. The path between the source node and the destination node is determined by the following procedure:

(1) Start at the source node.

(2) Examine the potentials of the adjacent nodes.

(3) Go to the node with the lowest potential. If two or more nodes have the same lowest potential, arbitrarily choose one of them.

(4) If the destination node is reached, then stop. Otherwise, go to (2).

Fig. 1 also shows the node potentials when it is specified that the current source $J = 1$ (A) and the resister = 1 (ohm). In the first iteration, for instance, the potentials of nodes 2 and 4 are compared to determine the next node. Since node 2 has a lower potential value (-0.571 < -0.429), it is chosen as the next node for the packet to be transferred to. Next, the potentials of nodes 3 and 5 are compared to determine the next node. Since both nodes have the same potential (-0.857), one can choose arbitrarily one of them. In this example we choose node 5. In Fig. 1, the path obtained by the preceding procedure is indicated by circles. If the link marked with a cross is heavily congested or faulty, the packet is transferred by choosing the node with the lowest potential from those connected by the remaining links. The detour path is indicated by triangles. Potential routing anticipates that *the lower the potential a node has, the closer it is to the destination.*

3. Adaptive Routing Based on Node Potentials

Consider the network shown in Fig. 2. Assume that there exist n paths Q_k ($1 \leq k \leq n$) from a source node S to a destination node D, and that each path Q_k contains h_k-1 intermediate nodes. In other words, h_k hops are needed to go from S to D along path Q_k. For the purpose of analysis we make the following further assumptions:

(1) All links have the same service capacity C (bits/sec).
(2) The packet length has the mean value 1/L (bits/packet) and follows an exponential distribution.
(3) The packets arriving at S follows

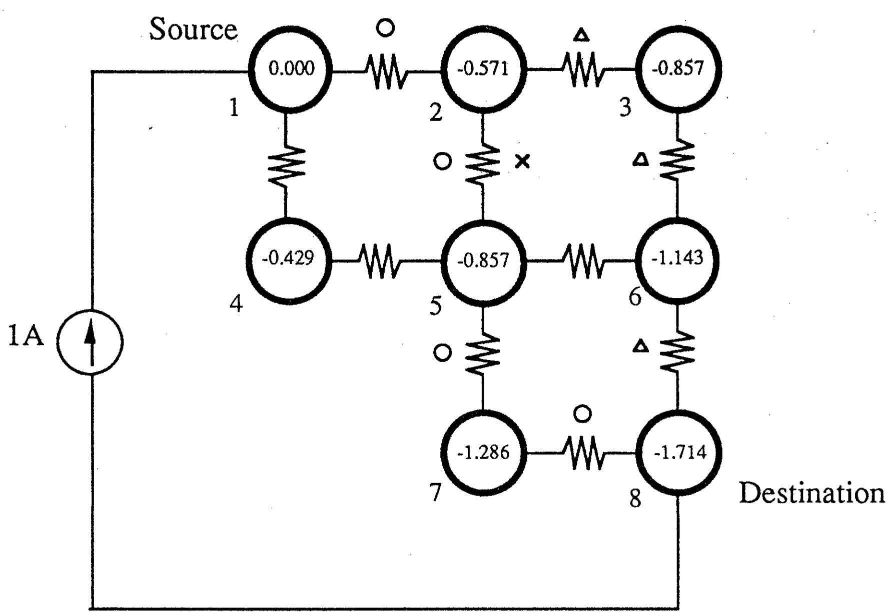

Fig. 1

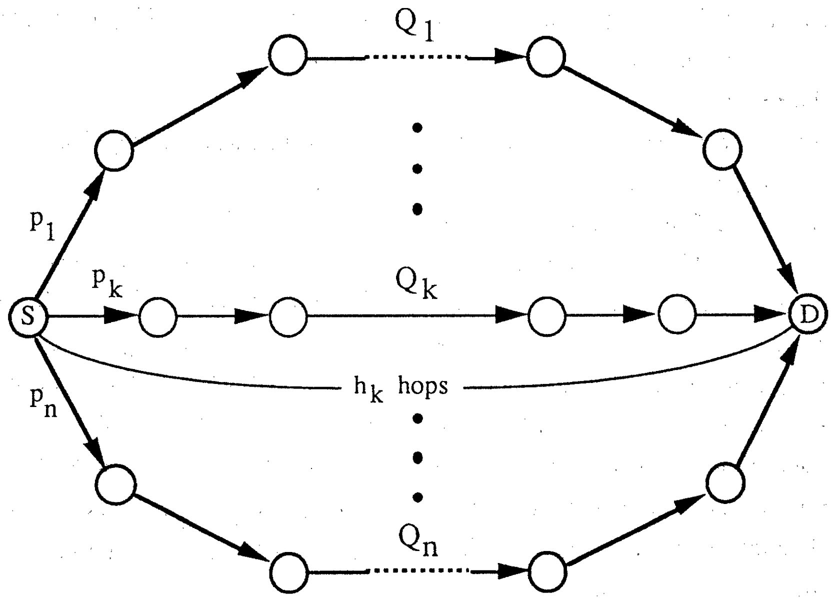

Fig. 2

Poisson distribution with a mean arrival rate of R (packets/sec).

(4) The packets are distributed to path Q_k with probability p_k.

(5) The stationary state is considered.

The network presented here is the same as n series connection of M/M/1 queues that are connected in parallel. Since the departure process of M/M/1 again follows a Poisson distribution, the time T_k taken to go from S to D along path Q_k is given by

$$T_k = \frac{h_k}{CL - p_k R} \qquad (1)$$

The average transfer time T is defined by

$$T \equiv \sum_{k=1}^{n} (p_k T_k)$$

$$= \sum_{k=1}^{n} \frac{p_k h_k}{CL - p_k R} . \qquad (2)$$

The optimum distribution factor $\{p_k\}$ is derived by using Lagrange's multiplier.[4] Defining the utilization rate $\rho_k \equiv \frac{p_k R}{CL}$, we obtain the normalized transfer latency τ_k as

$$\tau_k = \frac{h_k}{1-\rho_k} \qquad (3)$$

Clearly, it is wise to select the path Q_k that has the smallest τ_k.

In order to include the state of the traffic on the network in the routing control information, we consider the number of packets in the queue at the output link.[5] Let the mean number of packets in the M/M/1 queue system be q_k,

$$q_k = \frac{\rho_k}{1 - \rho_k} . \qquad (4)$$

Solving for ρ_k, we have

$$\rho_k = \frac{q_k}{1 + q_k} . \qquad (5)$$

The transfer latency τ_k is given as

$$\tau_k = \frac{h_k}{1 - \frac{q_k}{1+q_k}} = h_k(1+q_k) . \quad (6)$$

Since Potential routing regards the potential difference as the number of hops, the hop count h_k is replaced by $\frac{1}{\Delta V_k}$, which is the inverse of the potential difference between nodes. Therefore, $\frac{1 + q}{\Delta V_k}$ is used as the criterion for selecting the next node by which the routing controller should transfer the packet. In addition, to take Q-sensitivity[4] into account, this criterion is adjusted by adding a constant parameter α to the denominator, and $\frac{\Delta V_k}{1 + \alpha q_k}$ is used as the final criterion for selection. q_k is the number of packets in the output link k. When α is small, ΔV_k has a dominant effect and q_k has a smaller effect on the routing decision. This means that the static connectivity is emphasized. When α is large, on the other hand, the routing control is more sensitive to the state of the queue. Q-sensitivity is defined from this viewpoint.

4. Implementation

We describe the formal procedure for making a routing table. Although for simplicity we assume hereafter that all links have the same capacity, we can also make a routing table for a network that has various link capacities by assigning different resistance values to the adjacency matrix.

Let the set of nodes and the set of edges in network G be denoted by V and E, respectively.

Step 1: Construct the adjacency matrix $M = [m_{pq}]$ $(p, q \in V)$ of the network G, where $m_{pq} =$

1 if nodes p and q are adjacent

0 if nodes p and q are not adjacent. (7)

Step 2: As a preliminary to determining the node potentials, the coefficient matrix $W = [w_{ij}]$ $(i, j \in V)$ is calculated by Kirchhoff's law as follows:

$$w_{ii} = \sum_q m_{iq} \quad \text{(diagonal element)}$$

$$w_{ij} = - m_{ij} \quad (i \neq j). \qquad (8)$$

Step 3: As was described in Section 2, a current is made to flow between the source node and the destination node in order to obtain the node potentials. Let s and d $(s, d \in V)$ be the source node number and the destination node number, respectively. Let the vector representing the node potentials be

$$U(s,d) = [u_i]^t (s,d) \quad (i \in V) \quad (9)$$

where t indicates the transpose. The source node potential is defined as 0 (Volts), that is, $u_s(s,d) \equiv 0$. The following equation is obtained from Kirchhoff's first law:

$$W\,U(s,d) = J. \qquad (10)$$

For the network shown in Fig.3, let the source node be 5, and the destination node be 1. The system of equations is solved under the condition that $u_5(5,1) = 0$, and we obtain the node potentials

$U_5(5,1)$ = (-1.384, -0.887, -0.881, -0.371, 0, -0.397, -0.233, -0.303, -0.279, -0.256)

Step 4: Consider a node p, and let the set of nodes adjacent to p be A_p. Let r be one of the adjacent nodes of p ($r \in A_p$). For all r ($\in A_p$) , we have the potential difference $\Delta V_{pr}^{(s \to d)}$, where $(s \to d)$ means *from the source node s to the destination node d.*

At node 5 in Fig. 3, the potential differences: $\Delta V_{54}^{(5\to 1)}$, $\Delta V_{56}^{(5\to 1)}$, and $\Delta V_{57}^{(5\to 1)}$, which are for adjacent nodes 4, 6, and 7, respectively, are obtained by the vector $U_5(5,1)$ as follows:

$$\Delta V_{54}^{(5\to 1)} = -0.371$$
$$\Delta V_{56}^{(5\to 1)} = -0.397$$
$$\Delta V_{57}^{(5\to 1)} = -0.233 .$$

Note that routing tables are provided for all combinations of the source node and the destination node at every node. Consider a network with N nodes. The size of routing table for node p ($p \in V$) is $N \times (N-1) \times n_{A_p}$, where n_{A_p} is the number of adjacent nodes of p.

In potential routing, routing control is

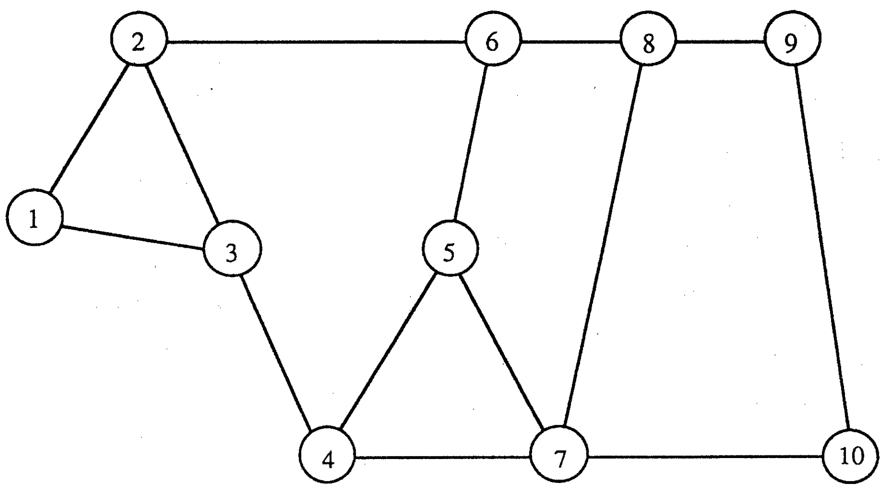

Fig. 3

performed by transferring a packet, successively selecting the adjacent node with the lowest $\frac{\Delta Vpr}{1 + \alpha q_{pr}}$, until the packet arrives at the destination node. q_{pr} is the number of packets on the link from the node p to the node r. Note that packets are never routed to the node r for which $\Delta V_{pr} \geq 0$. Consequently, the loop or ping-pong problem does not arise.

5. Evaluation

To verify the effectiveness of Potential routing, we performed simulations using the network model shown in Fig. 3. All simulation programs were written in C and performed on an IBM POWERstation RS/6000. For comparison, fixed routing and shortest queue + bias adaptive routing[1] are considered. Fixed routing always uses the shortest path between sources and destinations to transfer packets.

We simulated two traffic situations, balanced and unbalanced traffic. Balanced traffic is realized by assigning the source node and the destination node at random to each packet. Unbalanced traffic is realized by adding surge traffic, with node 1 as the source and node 10 as the destination, to balanced traffic. All simulations were run for about 100,000 packets delivered in the network.
The condition and the parameters of the simulation are as follows:
(1) The service capacity of each link is 9.6 kbps.
(2) The packet size is 800 bits/packet (fixed). Each packet contains header information such as source and destination.
(3) $\alpha = 1$.
(4) The generation of the packets follows a Poisson distribution.
(5) Queue size of output links is infinite.

Figures 4 and 5 show the results of simulations for the balanced and the unbalanced traffic situations, respectively. In the figures, *SQ+B* stands for Shortest Queue + Bias method. When the traffic is low, little difference between the fixed and the adaptive routing controls is observed. On the other hand, when the traffic is high or unbalanced, the mean packet transfer delay is reduced by using either shortest queue + bias routing or potential routing. Potential routing gives better results than shortest queue + bias routing.

6. Conclusion

We have presented an adaptive routing control method, potential routing, that is based on electrical circuit modeling. The computer network is regarded as an electrical circuit and the connectivities between nodes are represented by conductance, which provides a new criterion for adaptive routing control.

There are a couple of extensions of this research. These include: (1) packet transfer with priority scheme based on the node potential, and (2) centralized and decentralized algorithms for the update of routing tables according to the change of the network topology.

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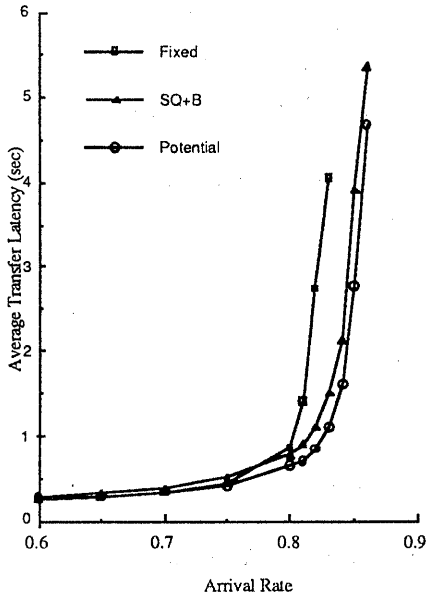

Fig. 4 Average transfer latency (balanced traffic)

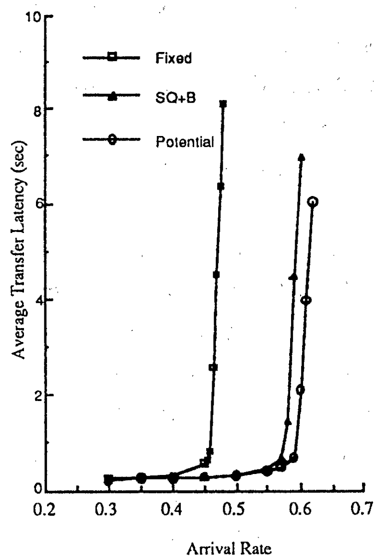

Fig. 5 Average transfer latency (unbalanced traffic)